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# Free-Space and Atmospheric Quantum Communications

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*Computational and Information Sciences Directorate, ARL*

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**14. ABSTRACT**

The quantum internet with free-space and atmospheric quantum channels is becoming a reality. Emerging from the early ideas of Feynman and his colleagues, quantum information science (QIS) technologies are under development around the world to construct the quantum internet. Destined to fulfill capabilities well beyond our current imagination, the quantum internet is being shaped by both the laws of quantum physics and the compelling needs for increased speed, bandwidth, and cybersecurity. Free-space and atmospheric quantum communications will play a critical role in extending the quantum internet to global use. Quantum information will be teleported through mobile information teleportation networks that necessarily will include satellites. Recent developments in quantum physics have the potential to add to free-space and atmospheric communications, a physical layer of quantum security, increased bandwidth, and speed beyond classical communications capabilities. Achieving a quantum communications internet with distributed quantum computing capabilities will first require research involving theory, experiments, and the development of proof-of-principle physics and engineering systems. This chapter introduces the reader to free-space quantum communications by providing both a review of the fundamental foundations of quantum communications as applied to free-space and the atmosphere and a review of representative free-space and atmospheric quantum communications experiments.

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# Chapter 10
# Free-Space and Atmospheric Quantum Communications

**Ronald E. Meyers, Keith S. Deacon and Arnold D. Tunick**

## 10.1 Introduction to Free-Space and Atmospheric Quantum Communications

The *quantum internet* with free-space and atmospheric quantum channels is becoming a reality [1, 2]. Emerging from the early ideas of Feynman and his colleagues [3], quantum information science (QIS) technologies are under development around the world to construct the *quantum internet*. Destined to fulfill capabilities well beyond our current imagination, the *quantum internet* is being shaped by both the laws of quantum physics and the compelling needs for increased speed, bandwidth, and cybersecurity. Free-space and atmospheric quantum communications will play a critical role in extending the *quantum internet* to global use (Fig. 10.1). Quantum information will be teleported through mobile *information teleportation networks* that necessarily will include satellites. Recent developments in quantum physics have the potential to add to free-space and atmospheric communications, a physical layer of quantum security, increased bandwidth, and speed beyond classical communications capabilities. Achieving a quantum communications internet with distributed quantum computing capabilities will first require research involving theory, experiments, and the development of proof-of-principle physics and engineering systems. This chapter introduces the reader to free-space quantum communications by providing both a review of the fundamental foundations of quantum communications as applied to free-space and the atmosphere (Sect. 10.2) and a review of representative free-space and atmospheric quantum communications experiments (Sect. 10.3).

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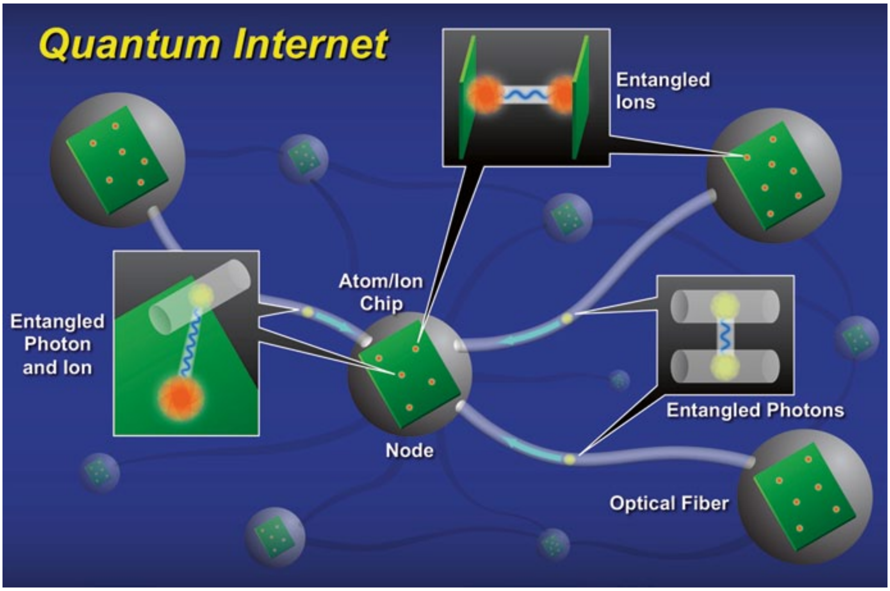


**Fig. 10.1** Quantum Internet concept depiction by Ronald E. Meyers, Keith S. Deacon, and Arnold D. Tunick, US Army Research Laboratory (2011) [4]

## 10.2 Fundamentals for Free-Space Quantum Communications

### *10.2.1 Introduction*

Physics strives to describe the laws that govern the evolution of the universe. A key tenet of physics is that the truth of any physical law must be tested by experiments. Proposed hypotheses are tested before a theory is formed that fairly describes the evolution in space and time of physical phenomena. Although nature is very complex, relatively few physical laws are needed to describe many of its facets. Einstein's theories of special and general relativity and quantum physics hold special places among the physical laws. Relativity has been proven on the large scale and seems to govern how stars and planets evolve while quantum physics has been the most effective in describing how particles and waves behave at the atomic and subatomic scales. The study of the full reconciliation of these theories is called quantum relativity. Nevertheless, enough is known about quantum physics and relativity to implement effective free-space atmospheric quantum communications systems. In other words, although we don't know everything, and there will be many more surprises, we know enough now to implement systems that are better in some important ways than current systems which are based on the classical understanding of physics and engineering. In 1935, Einstein in his famous EPR paper [5] raised the question of whether quantum mechanics gives a complete description of the universe. In the paper Einstein described the quantum mechanical behavior of two quantum particles which when separated by great distances had the state of one particle respond to changes of state of the other particle. Einstein also said that such a nonlocal effect, later known as the "EPR Effect," should be tested by experiment to determine if it was correct and if it corresponded to what quantum mechanical theory had predicted. In the 1970's and since, experiments have shown that the EPR effect of entanglement does indeed exist [6, 7]. Einstein described this effect as "Spooky action at a distance." It has become clear to many scientists that quantum mechanical effects such as entanglement and teleportation can be harnessed in quantum communications to enhance the security, bandwidth, compression, movement, and storage of information. In the following sections we will provide an introduction to the fundamentals needed to begin the investigation of free-space quantum communications. While they at first may find the concepts strange and the notation unfamiliar, engineers will find that they can harness the power of quantum physics for the development of free-space and atmospheric quantum communications systems.

### *10.2.2 Fundamentals*

The fundamentals of quantum physics describe the properties of quantum particles and quantum wavefunctions. Classical particles, such as a baseball, can be described by Newtonian physics where each particle simultaneously has a precise position and momentum. However, quantum particles such as photons and electrons have an uncertainty associated with both position and momentum such that quantum's uncertainty relationship holds, $\frac{\hbar}{2} \le \Delta x \Delta p$, where $\hbar$ is Planck's constant over $2\pi$ [8, 9]. Experimental measurements of position and momentum always note a variability in the measured values. Thousands of careful experiments have verified this relationship. Quantum particles are said to have both particle and wave properties. When a photon detector responds with a "click" it is measuring a photon in the sense of a particle. When light passes through a double slit and interferes, the light is exhibiting its interference wave properties. When a series of single photons are passed though a double slit the same interference patterns are measured. The way to describe the evolution of quantum properties has relied upon the construct of the wavefunction, $\Psi$. The wavefunction is in general a complex function having both real and imaginary values. When the wavefunction is multiplied by its complex conjugate, $\Psi^* \Psi$, it forms a positive function which when normalized gives the probability of the quantum particle being found in a particular state. In the case of a photon, the probability may describe where the photon is likely to be found in space. It is a peculiar property of quantum physics that the Fourier transform of the wavefunction in configuration space gives the wavefunction in momentum space. Position and momentum are called conjugate variables. Before we go further let us discuss the quantum mathematical background and formalism.

**Quantum Mathematical Background and Formalism** Quantum mathematical operations may use symbols and notation that are unfamiliar to the engineer. In this section we present notation and symbols often used in describing and developing quantum physics, quantum communications, and quantum information. Dirac developed the physics "bra" and "ket" notation. A "bra" is written as $\langle\ |$ and can be thought of as a row vector, i.e., $\langle A| = [A_1\mathbf{e}_1 + A_2\mathbf{e}_2 + A_3\mathbf{e}_3]$ and a "*ket*", $|\ \rangle$ is a column vector $|B\rangle = \begin{pmatrix} B_1\mathbf{e}_1 \\ B_2\mathbf{e}_2 \\ B_3\mathbf{e}_3 \end{pmatrix}$ where the $\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_2$ are orthogonal unit vectors [8]. An inner product operation using bra–ket notation is written as $\langle A|B\rangle = A_1B_1 + A_2B_2 + A_3B_3$. Another operator that is used when considering composite systems of more than one particle is the tensor, or direct product operator $\otimes$. For a two particle composite system this operation acts as shown below:

$$|A\rangle \otimes |B\rangle = \begin{pmatrix} A_1\begin{pmatrix} B_1 \\ B_2 \end{pmatrix} \\ A_2\begin{pmatrix} B_1 \\ B_2 \end{pmatrix} \end{pmatrix} = \begin{pmatrix} A_1B_1 \\ A_1B_2 \\ A_2B_1 \\ A_2B_2 \end{pmatrix}. \tag{10.1}$$

Infinite dimensional systems can also be represented in "bra–ket" notation but instead of discrete vector type components the inner, outer, and direct products are integrals over functions.

*Exercise 10.1* Given that a horizontally polarized photon is $|H\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and a vertically polarized photon is $|V\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ work out the composite states $|H\rangle \otimes |H\rangle$, $|H\rangle \otimes |V\rangle$, $|V\rangle \otimes |H\rangle$, and $|V\rangle \otimes |V\rangle$ [8].

10.1 Answer:

Using Eq. (10.1) the answers are,

$$|H\rangle \otimes |H\rangle = \left|\begin{pmatrix} 1 \\ 0 \end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix} 1 \\ 0 \end{pmatrix}\right\rangle = \begin{pmatrix} 1\begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ 0\begin{pmatrix} 1 \\ 0 \end{pmatrix} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$|H\rangle \otimes |V\rangle = \left|\begin{pmatrix} 1 \\ 0 \end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix} 0 \\ 1 \end{pmatrix}\right\rangle = \begin{pmatrix} 1\begin{pmatrix} 0 \\ 1 \end{pmatrix} \\ 0\begin{pmatrix} 0 \\ 1 \end{pmatrix} \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

$$|V\rangle \otimes |H\rangle = \left|\begin{pmatrix}0\\1\end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix}1\\0\end{pmatrix}\right\rangle = \begin{pmatrix}0\begin{pmatrix}1\\0\end{pmatrix}\\1\begin{pmatrix}1\\0\end{pmatrix}\end{pmatrix} = \begin{pmatrix}0\\0\\1\\0\end{pmatrix}$$

$$|V\rangle \otimes |V\rangle = \left|\begin{pmatrix}0\\1\end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix}0\\1\end{pmatrix}\right\rangle = \begin{pmatrix}0\begin{pmatrix}0\\1\end{pmatrix}\\1\begin{pmatrix}0\\1\end{pmatrix}\end{pmatrix} = \begin{pmatrix}0\\0\\0\\1\end{pmatrix}.$$

Alternately, the horizontally polarized photon can be expressed as $|H\rangle = \begin{pmatrix}H\\0\end{pmatrix}$

and the vertically polarized photon can be expressed as $|V\rangle = \begin{pmatrix}0\\V\end{pmatrix}$

so that the composite states can now be written as

$$|H\rangle \otimes |H\rangle = \left|\begin{pmatrix}H\\0\end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix}H\\0\end{pmatrix}\right\rangle = \begin{pmatrix}H\begin{pmatrix}H\\0\end{pmatrix}\\0\begin{pmatrix}H\\0\end{pmatrix}\end{pmatrix} = \begin{pmatrix}HH\\0\\0\\0\end{pmatrix}$$

$$|H\rangle \otimes |V\rangle = \left|\begin{pmatrix}H\\0\end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix}0\\V\end{pmatrix}\right\rangle = \begin{pmatrix}H\begin{pmatrix}0\\V\end{pmatrix}\\0\begin{pmatrix}0\\V\end{pmatrix}\end{pmatrix} = \begin{pmatrix}0\\HV\\0\\0\end{pmatrix}$$

$$|V\rangle \otimes |H\rangle = \left|\begin{pmatrix}0\\V\end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix}H\\0\end{pmatrix}\right\rangle = \begin{pmatrix}0\begin{pmatrix}H\\0\end{pmatrix}\\V\begin{pmatrix}H\\0\end{pmatrix}\end{pmatrix} = \begin{pmatrix}0\\0\\VH\\0\end{pmatrix}$$

$$|V\rangle \otimes |V\rangle = \left|\begin{pmatrix}0\\V\end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix}0\\V\end{pmatrix}\right\rangle = \begin{pmatrix}0\begin{pmatrix}0\\V\end{pmatrix}\\V\begin{pmatrix}0\\V\end{pmatrix}\end{pmatrix} = \begin{pmatrix}0\\0\\0\\VV\end{pmatrix}.$$

*Exercise 10.2*

If a photon is in an arbitrary polarization state $|A\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$

what are the composite states $|H\rangle \otimes |A\rangle$ and $|A\rangle \otimes |V\rangle$?

10.2 Answer: Again, following Eq. (10.1) the answers are

$$|H\rangle \otimes |A\rangle = \left|\begin{pmatrix} 1 \\ 0 \end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix} \alpha \\ \beta \end{pmatrix}\right\rangle = \begin{pmatrix} 1\begin{pmatrix} \alpha \\ \beta \end{pmatrix} \\ 0\begin{pmatrix} \alpha \\ \beta \end{pmatrix} \end{pmatrix} = \begin{pmatrix} \alpha \\ \beta \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} H\alpha \\ H\beta \\ 0 \\ 0 \end{pmatrix}$$

and

$$|A\rangle \otimes |V\rangle = \left|\begin{pmatrix} \alpha \\ \beta \end{pmatrix}\right\rangle \otimes \left|\begin{pmatrix} 0 \\ 1 \end{pmatrix}\right\rangle = \begin{pmatrix} \alpha\begin{pmatrix} 0 \\ 1 \end{pmatrix} \\ \beta\begin{pmatrix} 0 \\ 1 \end{pmatrix} \end{pmatrix} = \begin{pmatrix} 0 \\ \alpha \\ 0 \\ \beta \end{pmatrix} = \begin{pmatrix} 0 \\ \alpha V \\ 0 \\ \beta V \end{pmatrix}.$$

**Quantum Wavefunctions** Wavefunctions represent the probability amplitudes used to describe the state of a quantum particle. Quantum particles are physical entities such as photons, electrons, protons, and neutrons. They are often expressed using Dirac's bra–ket notation where the state of a particle can be written as

$$|\Psi\rangle = \sum_{i=1}^{N} c_i |\phi_i\rangle$$

where the $c_i$ and $\phi_i$ are the amplitude and quantum state respectively. The $c_i$ can be complex valued and $\phi_i$ can be a measurable state such as a horizontal or vertical polarization for a photon or spin up/spin down for an electron spin. The probability that a quantum particle will be measured in particular states is given by

$$P = \Psi^* \Psi.$$

Wavefunction evolution can be described by a Schrodinger equation such as the one below

$$i\hbar \frac{\partial}{\partial t} \Psi(\mathbf{r},t) = -\frac{\hbar^2}{2m} \nabla^2 \Psi(\mathbf{r},t), \tag{10.2}$$

where $\hbar$ is Planck's constant over $2\pi$, $m$ is mass, $t$ is time and $\mathbf{r}$ is the position in space. A more accurate wavefunction propagation or evolution equation for free-space quantum communications would have to include terms added to Eq. (10.2) to incorporate the effects of absorption, scattering, and index of refraction fluctuations as functions of space and time. It must be kept in mind that turbulence is not stationary, is inhomogeneous, and is a dynamic function of space and time.

*Exercise 10.3* The Schrodinger equation describes the evolution of the quantum wavefunction in space and time. How many space boundary conditions and time initial conditions are needed to solve this equation?

*Exercise 10.4* Assume that the Schrodinger equation solution is a product of space only and time only factors. For a periodic time solution to the Schrodinger equation write the differential equation for the space dependent solution in one space dimension.

*Exercise 10.5* Solve for the space dependent wavefunction solutions given a finite bounded domain. What are the consequences for bounded versus unbounded domains?

**Quantum Particles** There are two primary classifications of quantum particles. Bosons are spin-1 particles and fermions are spin-1/2 particles. The spin numbers are measures of the quantized angular momentum. Multiple fermions cannot occupy the same quantum state while there can be any number of bosons in a particular quantum state.

**Modes** A mode is best described as a fundamental solution of a wave equation. The frequency and momentum of a travelling electromagnetic plane wave in two space dimensions and time is given by

$$\vec{E}(k_x, k_y, \omega) = e^{i\omega t}\left(e^{ik_x x + ik_y y}\right) \tag{10.3}$$

and with $k = \dfrac{\omega}{c}$, we can say that $k_x = k\cos\theta$ and $k_y = k\sin\theta$ provided that $k^2 = k_x^2 + k_y^2$ [9]. In general, electromagnetic waves undergo spherical radiation from an atom but after travelling a long distance may be approximated by a plane wave over a small sector.

**Conjugate Variables** Quantum variables have certain properties that are conjugate to each other such that the more information and accuracy that is known about one of the properties the less is known about the conjugate property. The relationship between these conjugate properties is governed by the Heisenberg uncertainty principle $\dfrac{\hbar}{2} \le \Delta x \Delta p$. Other conjugate variable pairs include energy-time and particle number-phase [10].

**Operators** Quantum operators are mathematical functions that act on quantum wavefunctions to describe properties such as position and momentum [11]. Operators in quantum physics are often noted as $\hat{A}$ where $\hat{A}$ is associated with an observable, i.e., a measurable quality of a quantum system. Examples of operators include $\hat{\mathbf{p}} = -i\hbar\nabla$ for momentum and $\hat{L} = -i\hbar\mathbf{r}\times\nabla$ for angular momentum. Another notable pair of operators in quantum mechanics are the creation operator $a^\dagger$ and the annihilation operator $a$ that are often used to describe the addition or subtraction of a fixed quanta of energy to a system.

### 10.2.3 The Concepts of Information Content and Quantum Information

The fundamental unit of quantum information is the qubit [12, 13]

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

with $|\alpha|^2 + |\beta|^2 = 1.$ Unlike a classical bit, a qubit has the property of being both 0 and 1 at the same time. This property allows qubits to be operated on over both amplitude values of the $\alpha|0\rangle + \beta|1\rangle$ superposition at the same time. Qubits may also be combined to allow for the representation of large quantities of information. A single qubit can hold 2 bits of classical information in superposition, 2 qubits 4 bits of classical information and $n$ qubits can represent $2^n$ bits of classical information. However, when the qubit is measured the outcome will be a single bit value of either 0 or 1.

### 10.2.4 Quantum Optics

The nature of light having particle and wave properties is still somewhat mysterious. Viewed as a wave, engineers often characterize light as electromagnetic waves that propagate and scatter after being emitted. However, quantum optics uses operators that are distinctly different from the usual terms in the conservation equations of classical physics. Quantum optics also deals with measurements made at separated time and space points which show that light has a property of coherence and distant entanglement. Glauber received the 2005 Nobel prize for his work on quantum optical coherence which elucidated the space and time quantum effects of light in which he recognized and expounded the important role of measurements in the quantum process [14]. The recent textbook by Shih [15] provides an important reference for the current state of quantum optics. In the following, we outline a few representative features of quantum optics that are relevant to free-space atmospheric quantum communications. However, this exciting field is growing quickly and we must expect many more contributions in the years to come.

**Table 10.1** Hanbury-Brown Twiss experiment results

| Light source | HBT result |
|---|---|
| Coherent (Laser) | No Correlation [11] |
| Incoherent (Thermal) | Positive Correlation (Peak) [15] |
| Non-classical (Entangled) | Negative Correlation (Dip) [15] |

### *10.2.5 Quantum Sources*

All light is quantum all of the time but not all measurements and analysis readily reveal distinctly quantum properties of light. There are various sources of light including incoherent radiation, coherent radiation, and nonclassical sources of radiation. Incoherent sources of radiation are sources of light that are most familiar to us. Light bulbs, lamps, and the sun are all sources of incoherent thermal light. These incoherent light sources typically have broad spectral characteristics. We note that pseudo-thermal light [16, 17] produced by the transmission of laser light through a scattering media such as a rotating ground glass plate has a much narrower spectral bandwidth than the more commonly experienced sources of thermal radiation. Coherent sources such as lasers, are available in a variety of wavelengths and can be used for many quantum applications. Nonclassical sources of light include entangled photons, produced by nonlinear processes such as spontaneous parametric down conversion (SPDC) and four wave mixing, and squeezed light where there is a trade-off between phase information and photon number information. To highlight the differences between coherent, thermal, and nonclassical light, Hanbury-Brown and Twiss (HBT) two-photon interferometry is often used [11, 14, 18]. An HBT experiment is performed when light is split by a beam splitter toward two detectors. The detectors measure incident photons and the times that the measurements took place. The measurements at the two detectors are then correlated with each other, with results shown in Table 10.1.

The coincident deviations of the intensities from the mean of each detector tend to be positively correlated for incoherent light and negatively correlated (anticorrelated) for nonclassical light [15]. The coincident deviations of the intensities for coherent light tend to be uncorrelated. Variations from standard experimental conditions may produce results that vary from these.

### *10.2.6 Quantum Measurement Processes*

There are several important aspects with regard to quantum measurement processes. The probabilities for measuring a quantum state can be given by

$$P(n) = \sum_n |c_n|^2 |\psi_n\rangle\langle\psi_n|$$

where the $\psi_n$ correspond to the quantum state to be measured, such as the horizontal or vertical polarization of a photon, and the $c_n$ are the wavefunction amplitudes for that quantum state. As an example if one prepares a photon in a diagonal polarization $(\nearrow)$ and then performs a measurement for horizontal or vertical in the perpendicular basis $(\perp)$, the $c_n$ are equal to $\frac{1}{\sqrt{2}}$ and there is a 50 % probability that the photon will be measured as as either an $H$ or a $V$ photon. When measuring a composite quantum system made up of two states the Bell basis measurement is often used [8, 13]. The four possible Bell basis states using polarization are

$$\begin{aligned}
\psi^{+} &= \frac{1}{\sqrt{2}}\left(|H_A\rangle|V_B\rangle + |V_A\rangle|H_B\rangle\right)\\
\psi^{-} &= \frac{1}{\sqrt{2}}\left(|H_A\rangle|V_B\rangle - |V_A\rangle|H_B\rangle\right)\\
\phi^{+} &= \frac{1}{\sqrt{2}}\left(|H_A\rangle|H_B\rangle + |V_A\rangle|V_B\rangle\right)\\
\phi^{-} &= \frac{1}{\sqrt{2}}\left(|H_A\rangle|H_B\rangle - |V_A\rangle|V_B\rangle\right).
\end{aligned} \tag{10.4}$$

The following identities also hold for the Bell states:

$$\begin{aligned}
|H_A\rangle|H_B\rangle &= \frac{1}{\sqrt{2}}\left(|\phi^{+}\rangle + |\phi^{-}\rangle\right)\\
|H_A\rangle|V_B\rangle &= \frac{1}{\sqrt{2}}\left(|\psi^{+}\rangle + |\psi^{-}\rangle\right)\\
|V_A\rangle|H_B\rangle &= \frac{1}{\sqrt{2}}\left(|\psi^{+}\rangle - |\psi^{-}\rangle\right)\\
|V_A\rangle|V_B\rangle &= \frac{1}{\sqrt{2}}\left(|\phi^{+}\rangle - |\phi^{-}\rangle\right).
\end{aligned} \tag{10.5}$$

A Bell measurement is a coincidence measurement that discriminates the actual state of an unknown two-photon polarization system. A primary distinction between entangled states and nonentangled states is that an entangled state is not factorizeable into the product of two states:

$$\frac{1}{\sqrt{2}}\left(|H_A\rangle|V_B\rangle - |V_A\rangle|H_B\rangle\right) \neq \left(|H_A\rangle \pm |V_A\rangle\right) \otimes \left(|H_B\rangle \pm |V_B\rangle\right).$$

This nonfactorizeability makes the entangled states quite powerful for quantum communications, quantum computing, and quantum imaging [15, 19]. In this case we are talking about photons that have polarization entangled states. The quality of a quantum measurement is often reported in terms of "fidelity." A quantum state is said to be "faithful" if the function $F(p,q)=\sqrt{pq}$ is sufficiently close to 1, where $p$ indicates the probability that quantum state $|\Psi\rangle$ has been prepared and $q$ is the probability that state $|\Phi\rangle$ was measured. This idea may also be reversed to say if state $|\Phi\rangle$ was measured then the "fidelity" of how well $|\Psi\rangle$ was prepared can be assessed [13].

Another measurement technique is that of the positive operator valued measurement (POVM) in distinction to projective measurements [13, 20, 21]. POVMs reduce the probability of inconclusive measurements with the use of ancilla modes. For instance, if photons that are polarized either horizontally ($H$) or $+45^\circ$ in equal amounts are passed through a $V$ polarizer or a $-45^\circ$ polarizer, then the one that passes through the $V$ polarizer must have been a $+45^\circ$ photon and if the photon passes through the $-45^\circ$ polarizer it must have been a $H$ polarized photon. This would yield a 25 % chance to determine the polarization state of the transmitted photon. With the addition of certain "ancilla" modes of the optical fields a POVM can determine the polarization state of the transmitted photon for this example with a probability of 29.3 % [13].

### 10.2.7 Quantum Squeezing

Quantum squeezing occurs when a process is applied to the quantum system that adjusts the relative values of a conjugate variable pair. Quantum squeezed light has been demonstrated using laser and nonlinear materials to alter the uncertainty between photon number and phase $\frac{\hbar}{2}\le \Delta n\Delta\phi$ where the uncertainty in the photon number is decreased while the uncertainty of the phase is increased. Quantum squeezed states are often used for applications in quantum metrology as well as for continuous variable QKD implementation [22].

### 10.2.8 Measurement Bases Used in Quantum Protocols

This section discusses the measurement bases used in quantum protocols. Measurement bases for quantum communications protocols include linear polarizations $|\Psi\rangle=\alpha|H\rangle+\beta|V\rangle$, circular polarizations $|\Psi\rangle=\alpha|R\rangle+\beta|L\rangle$, orbital angular momentum $|\Psi\rangle=\alpha|L_0\rangle+\beta|L_1\rangle$ ($L_n$ in this superposition indicate the Laguerre mode), and time-bin superpositions $|\Psi\rangle=\alpha|L\rangle+\beta|S\rangle$ where $L$ and $S$ and refer to a superposition of long and short paths propagated by a quantum particle through an unbalanced Mach–Zehnder interferometer. Any quantum basis that has a measurable superposition with at least two possible results may be used in a quantum protocol.

**Table 10.2** Polarization transmission

| Polarization Filter Orientation | Transmission Probability |
|---|---|
| H | 0% |
| V | 100% |
| +45 | 50% |
| −45 | 50% |

**Coherence and Incoherence** Coherence and incoherence can be defined in the following manner. Light may be said to be temporally coherent if the distance $c\tau_c$ is much greater than all of the optical path-length differences encountered in an optical system. The coherence time $\tau_c$ is defined as

$$\tau_c = \int_{-\infty}^{\infty} | g(\tau) |^2 d\tau$$

where the degree of temporal coherence is

$$g(\tau) = \frac{G(\tau)}{G(0)} = \frac{\langle U^*(t)\, U(t+\tau)\rangle}{\langle U^*(t)\, U(t)\rangle}$$

and $U$ is the complex wavefunction of the light.

Similarly, light may be described as being spatially coherent if the *coherence area* of the light is larger than the largest aperture of an optical system. The *coherence area* is related to the complex degree of coherence

$$g(\mathbf{r}_1.\mathbf{r}_2) = \frac{G(\mathbf{r}_1.\mathbf{r}_2)}{\sqrt{\langle I(\mathbf{r}_1)\rangle \langle I(\mathbf{r}_2)\rangle}},$$

where $G(\mathbf{r}_1.\mathbf{r}_2)$ is the mutual intensity and is equal to $\left\langle U^*(\mathbf{r}_1,t)\, U(\mathbf{r}_2,t)\right\rangle$ and the $I$ values are the intensities measured at positions $\mathbf{r}_1$ and $\mathbf{r}_2$ [14, 23].

**Polarization** Polarization in optics is generally associated with the $E_x$ and $E_y$ components of an electromagnetic plane wave propagating in the z direction. In quantum communications, linear polarization is restricted to two orthogonal bases; the Horizontal-Vertical (H-V) basis or the $45^\circ$ rotated basis (A-D). The properties of these linear polarizations are that a particular polarization has a 100% chance to propagate through a polarization filter aligned parallel with the polarization of the light and 0% chance to propagate through a polarization filter aligned in a direction orthogonal to the polarization of the light. The orientation of the polarizing filter may uniformly vary the transmission from 0% to 100%. For instance, a photon with vertical polarization has the transmission probabilities for a prescribed set of polarization filter orientations that are shown in Table 10.2.

Polarization is a useful property for quantum information purposes as a simple way to create and manipulate a qubit, where one polarization would (when measured) take the logical value of 0 and the other measurement a value of 1. However, unlike classical logical bits a single qubit is simultaneously both 0 and 1 in superposition until measured. For instance, an equal superposition of 0 and 1 as a polarization qubit could be

$$|\Psi\rangle = \alpha|H\rangle + \beta|V\rangle$$

where $|H\rangle = 0$, $|V\rangle = 1$ and $\alpha = \beta = \frac{1}{\sqrt{2}}$ [13, 23].

**Energy-Time Entanglement** Energy-time entanglement and time-bin entanglement are closely related. Two particles can be energy-time entangled. Earlier we mentioned that photons can be polarization entangled. Quantum particles may be entangled in one or more properties. Energy-time entanglement has been achieved using an unpulsed pump laser and time-bin entanglement has been achieved using a pulsed laser [24]. Time-bin entanglement is a state where photons are entangled in between long and short paths of an unbalanced interferometer. That is, in quantum systems, not only can quantum particles be entangled but also their paths can be entangled. This last quantum property gives quantum scientists and engineers a lot to work with in designing quantum communications systems that exploit entanglement.

**Quantum Coherence** Quantum coherence refers to a property associated with photons or other quantum particles. Quantum coherence represents an ideal quantum state where the uncertainty between conjugate variables are a minimum and are equally distributed [14]. For example, position $x$ has an uncertainty of $\Delta x$ and momentum $p$ has an uncertainty $\Delta p$ and the uncertainties are both, minimum and equally distributed between $\Delta x$ and $\Delta p$ in the equation, e.g., when $\frac{\hbar}{2} = \Delta x \Delta p$. The closer a system is to this ideal uncertainty relationship the more coherent it is said to be. For example a laser is often a very coherent system. Conversely, when the product $\Delta x \Delta p$ is much greater than $\frac{\hbar}{2}$ the system is said to be more incoherent. For example, thermal light sources such as the sun or an incandescent light bulb would radiate incoherent light. Pseudo-thermal sources created by propagating a laser beam through a rapidly rotating ground glass plate also can produce light that has incoherent properties [16, 17]. Pseudo-thermal sources provide a convenient experimental source of partially coherent or incoherent radiation with relatively large coherence time and space scales.

**Quantum Decoherence and Quantum Memory** Quantum memories need to be able to preserve a quantum state long enough for operations to be performed on that quantum state. Quantum decoherence is the effect that occurs when quantum states interact with the environment and lose their quantum interference effects. Better quantum memories preserve a quantum state for a longer time [25, 26].

### *10.2.9 Spontaneous Parametric Downconversion (SPDC) and Upconversion*

For quantum detection of correlated photons pairs at greater detection efficiencies, spontaneous parametric downconversion (SPDC) and upconversion methods have been developed [15, 27, 28]. Generally speaking the SPDC process employs a $\chi^2$ nonlinearity of a material such as beta-barium borate (BBO) or lithium borate (LBO) to split a pump photon into two photons subject to the condition

$$\nu_P = \nu_s + \nu_i$$

where $\nu_P$ is the frequency of the pump photon and $\nu_s$ and $\nu_i$ are the frequencies of the two downconverted photons. The frequencies of $\nu_s$ and $\nu_i$ need not be equal to each other which has useful applications for quantum communications. The subscripts *s* and *i* represent signal and idler respectively. Historically "signal" refers to the higher frequency anti-Stokes photon and "idler" is the lower frequency Stokes photon [29]. Similarly, upconversion utilizes a nonlinear process whereby a photon, say at the telecommunications wavelengths (1300–1500 nm) where detector efficiency is low and noisy, is upconverted to the visible or near IR where silicon based photon detectors have much higher efficiencies and less noise. In this case the equation appears as

$$\nu_T + \nu_P = \nu_U$$

where $\nu_T$ is the frequency of the telecommunications wavelength photon and $\nu_U$ is the upconverted detector photon. The upconversion pump frequency at $\nu_P$, the nonlinear media and the tuning of the phase-matching conditions must all be chosen to optimize the efficiency of the upconversion to $\nu_U$ for the particular detectors involved. We note that the relationship between the frequency ν and wavelength λ [9, 30] is given by the following:

$$\begin{aligned} \nu &= \frac{c}{\lambda} \\ \lambda &= \frac{c}{\nu}. \end{aligned} \tag{10.6}$$

There is research to develop better entangled photon sources for free-space applications [31] where the wavefunctions for the polarization entangled photons generated by this implementation are of the form

$$|\Psi(\phi)\rangle = \frac{1}{\sqrt{2}}(|V_{\lambda_s}V_{\lambda_i}\rangle + e^{i\phi(\lambda_s,\lambda_i)}|H_{\lambda_s}H_{\lambda_i}\rangle)$$

where $\lambda_s$ and $\lambda_i$ are the wavelengths of the downconverted photons and $\phi$ is a relative phase, typically caused by birefringence, between the two wavelengths in their device. In practice, the phase $\phi$ must be considered, however it is often left out of theory formalism to simplify the presentation.

### *10.2.10 Random Number Generation By Quantum Physics Versus the Pseudo-Random Number Generation of Classical Encryption*

Pseudo-random number generators (PRNG) are commonly used in a computational environment. Monte-Carlo numerical methods are often used for approximating solutions to problems with very large numbers of degrees of freedom. The typical PRNG uses one or more “seed” numbers and performs various bit shift and “or” operations on the binary representation of the number to provide the next “random” number in the sequence [32]. This type of random number generator will eventually exhibit periodic behavior, i.e., repeating a sequence already generated. Furthermore, while most PRNGs can exhibit statistically valid “uniformity” up to becoming periodic, on other tests of statistics such as $\chi^2$ they may fail. A quantum random number generator (QRNG) depends on the inherently random result of the measurement of the physical state of a quantum system as discussed in Sect. 10.2.6. QRNGs cannot be periodic and they lack the biases of the classically computed pseudo-random number.

### *10.2.11 No-Cloning Theorem*

The *no-cloning* theorem in quantum physics describes the inability of linear processes to measure, copy and retransmit quantum information without destroying the superposed quantum state [13]. The no-cloning property uses the fundamentally important physics property of superposition to establish procedures that prevent an eavesdropper (Eve) from “listening” in on the communication between Alice and Bob without being detected. For instance, let us assume that Eve attempts to intercept polarization based quantum communications photons between Alice and Bob. Eve could attempt a so-called “measure and resend” attack on the quantum communications channel. In this instance Eve tried to act as Bob and randomly chose

**Table 10.3** No Cloning Example

| | Alice Transmission | Eve Measurement using Random Basis | Eve Resend | Bob Measurement using Random Basis |
|---|---|---|---|---|
| 1 | → | ↗ | ↗ | ↑ (Error!) |
| 2 | ↑ | ↘ | ↘ | ↑ |
| 3 | ↘ | ↑ | ↑ | ↑ (Error!) |
| 4 | ↗ | → | → | → (Error!) |

measurement bases and then retransmit to Bob a photon of the polarization that she measured. In principle, if Eve attempts to intercept photons and copy and resend with errors, then Alice and Bob would notice an increase in key errors thus indicating an eavesdropper. Unfortunately for Eve, but fortunately for Alice and Bob, she would be detected due to the consequences of the no-cloning property which prohibits an exact copy of a quantum state to be created. An example of four of the many possible outcomes for Alice, Bob, and Eve illustrating the effect of the no-cloning property is shown with the BB84 QKD [33] protocol in Table 10.3.

In each line of the table Alice is transmitting a photon with the indicated polarization. Eve attempts to eavesdrop by measuring those photons in a random basis and those measurement outcomes are indicated. Eve then retransmits a photon with the polarization she measured to Bob and his measurement in a random basis is indicated. The measurements at 1, 3, and 4 are identified as errors during the shared key generation process and alert Alice and Bob that there has been an attempt to eavesdrop on their quantum communications channel. While Bob measures in a randomly chosen basis to negotiate a key with Alice, the measurement by Eve using a random basis and resending to Bob introduces errors beyond those normally encountered by Alice and Bob when Eve is not present. While the no-cloning theorem applies to linear systems it does not necessarily apply to nonlinear cloning processes. Nevertheless, the no-cloning effect raises the bar for eavesdropper attacks.

There are other limitations for the security of quantum communications. For instance, it is possible to clone a quantum state using a non-linear process; a lossy channel between Alice and Bob can allow Eve to intercept quantum states and remain undetected; poor quantum efficiency of the detectors for Alice and Bob and interception of certain information can enable Eve to obtain the entire secret key [34, 35, 36].

### *10.2.12 Weak Coherence*

Weak coherence has been used in the context of quantum communications to describe the condition where a laser pulse contains on average much less than one photon per pulse. These weak coherent approaches suffer from the fact that the number of photons in a pulse generally follows Poisson distribution [11, 23]

$$p(n) = \frac{\langle n \rangle^n e^{-\langle n \rangle}}{n!}. \tag{10.7}$$

The Poisson distribution describes the probability for $n$ photons to be detected. $\langle n \rangle$ is the average number of photons in a given time interval $T$ and is related to the optical power $P$ as

$$\langle n \rangle = \frac{PT}{h\nu}.$$

It is fairly easy to see that for a given optical power, no matter how weak, there is a finite probability to have more than a single photon in a pulse. This means that QKD systems that use weak coherent pulses do not achieve the full level of security allowed by quantum physics.

*Exercise 10.6* Estimate the probability for two photons in a pulse, given the average number of photons per pulse being $(a)\ \langle n \rangle = 10,\ (b)\ \langle n \rangle = 1,\ (c)\ \langle n \rangle = 0.1$. Discuss the ramifications for QKD when Eve might intercept one of these excess photons.

10.6 Answer: Using Eq. (10.7) with the probability to detect $n=2$ photons per pulse we find for cases (a), (b), and (c) the following:

$$\begin{array}{ccc}
(a) & (b) & (c) \\
p(2) = \dfrac{(10)^2 e^{-10}}{2!} & p(2) = \dfrac{(1)^2 e^{-1}}{2!} & p(2) = \dfrac{(.1)^2 e^{-.1}}{2!} \\
= \dfrac{100e^{-10}}{2} & = \dfrac{1e^{-1}}{2} & = \dfrac{.01e^{-.1}}{2} \\
\simeq 2.27 \times 10^{-3} & \simeq 1.84 \times 10^{-1} & \simeq 4.52 \times 10^{-3}
\end{array}$$

### *10.2.13 Entangled Photon Quantum Communications*

In 1991, Ekert proposed a QKD protocol using entangled photons [37]. This has been experimentally demonstrated in 2000 [38]. However, another use of entangled photons for quantum communications is to utilize the quantum features of photons to enable quantum information over long distances in free-space or in fiber by entangling remote quantum memories [25, 26]. The quantum information stored in these two separated quantum memories can be used to teleport quantum information from one site to another. Teleportation with secure protocols is sometimes referred to as *tamper resistant* quantum communication because it is the entanglement itself that performs the transmission of the information in a quantum teleportation operation. The information that is sent over the classical channel really amounts to instructions on how to measure the receiver's quantum state to recover the teleported quantum information. Teleportation is discussed below.

**Table 10.4** Example using entangled photons for QKD

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Alice | 1 | 0 | 1 | 0 | 0 | 1 | … | 1 |
| Bob | 0 | 1 | 0 | 1 | 1 | 0 | … | 0 |

### *10.2.14 Quantum Cryptography and Quantum Key Distribution*

Quantum cryptography and quantum key distribution (QKD) are technologies that are being developed to exploit the quantum features of light and particles to send and to receive quantum information with the highest possible level of physical security. In the language of QKD, Alice, Bob, Charlie, and Eve refer to the sender, the receiver, a third participant, and the eavesdropper, respectively. As a simple example of quantum key generation, encryption and transmission, imagine that Alice and Bob each receive one part of an entangled pair of photons. For instance assume that the entangled photon is in the $|\Psi^{-}\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|H_A\rangle|V_B\rangle - |V_A\rangle|H_B\rangle\right)$ state. When Alice and Bob make their measurements each would measure the orthogonal polarization, i.e., if Alice measures a $|H\rangle$ then Bob must measure a $|V\rangle$. We can also assign 0's and 1's to the polarizations so that $|H\rangle = 0$ and $|V\rangle = 1$. After many measurements of these entangled photons Alice and Bob would each have a sequence of random bits (Table 10.4).

Using this shared sequence of random bits Alice can encode a message using an exclusive binary "or" (XOR) operation and transmit that message to Bob who has a binary sequence that he can use to decode the encrypted message. Some interesting QKD schemes are the following: BB84 [33], B92 [39], Ekert91 [37], and Yuen–Kumar (Alpha-Eta or Y00) [40].

**Protocols BB84 and B92** Two of the early QKD encryption protocols BB84 [33] and B92 [39] are reviewed in the following paragraphs.

The B92 QKD [39] protocol consists of the following steps:

1. Alice randomly chooses a polarization orientation for the photon she transmits as either Horizontal, $|H\rangle = |0\rangle$, or the $45^{\circ}$ rotated basis $|D\rangle = |1\rangle$. Alice keeps track of the 0's and 1's she has sent to Bob.
2. Bob randomly chooses to measure the photon in either the $V$ basis or the $-45^{\circ}$ basis and announces over a public channel if a measurement or a "no-measurement" result occurs.
3. When the key transmission is completed key sifting, a key reconciliation process, and tests of eavesdropping take place. The probabilities to make a measurement are indicated in Table 10.5.

*Exercise 10.7* Using the B92 protocol Alice transmits to Bob a random bit sequence and Bob makes measurements in the bases indicated in Table 10.6.

The sifted key of 011 in this example assumed that all of the basis choices made by Bob produced a measurement. There is a 50 % chance that any measurement attempted between the nonorthogonal bases could cause Bob to announce that a no-measurement (N) outcome occurred. Work out the sifted key by filling in the

**Table 10.5** B92 Example

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alice | Bit Value | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| | State | *H* | *H* | 45° | 45° | *H* | *H* | 45° | 45° |
| Bob | Basis | *V* | −45° | *V* | −45° | *V* | −45° | *V* | −45° |
| | Measurement Probability | 0 | 50% | 50% | 0 | 0 | 50% | 50% | 0 |

**Table 10.6** B92 Example

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alice | Bit Value | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| | State | *H* | 45° | *H* | 45° | *H* | 45° | 45° | *H* |
| Bob | Basis | *V* | −45° | *V* | *V* | −45° | −45° | −45° | −45° |
| | Measurement | *N* | *N* | *N* | *Y/N* | *Y/N* | *N* | *N* | *Y/N* |
| Shared | Key | | | | 0 | 1 | | | 1 |

**Table 10.7** B92 Example

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alice | Bit value | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| | State | *H* | *H* | 45° | *H* | 45° | 45° | *H* | *H* |
| Bob | Basis | *V* | – 45° | – 45° | *V* | *V* | – 45° | – 45° | *V* |
| | Measurement | ? | ? | ? | ? | ? | ? | ? | ? |
| Shared | Key | ? | ? | ? | ? | ? | ? | ? | ? |

blocks marked with "?" if Alice and Bob use the transmitted bits and basis shown in Table 10.7 under the assumption that all of Bob's basis choices produced a measurement. It should be noted that the B92 protocol has been shown to be insecure.

The BB84 QKD [33] protocol consists of the following steps:

1. Alice randomly chooses a bit value 0 or 1 and a polarization basis, rectilinear or diagonal, to transmit to Bob. Alice keeps track of the 0's and 1's and the basis she has sent to Bob.
2. Bob randomly chooses a basis to measure in and records the result of the measurement as a 0 or 1.
3. A process known as key sifting then occurs where Bob announces over a public channel the measurement bases used and Alice sends back a list of the valid bases chosen by Bob. No public announcement of the outcome of a measurement or the value sent by Alice is made.
4. When the key transmission is completed a key reconciliation process and tests of eavesdropping take place. The probabilities to make a measurement are indicated below in Table 10.8.

   In the above tables + indicates a measurement done in the H–V basis, × indicates a measurement performed in the rotated $45^{\circ}$ basis, → indicates a horizontally polarized photon, ↑ a vertical photon, ↗ a horizontal photon in a rotated $45^{\circ}$ basis, and ↘ is a vertical photon in a $45^{\circ}$ basis. When the symbols are combined, as in ↗↘ or →↑, this indicates that the photon state transmitted by Alice

**Table 10.8** BB84 Example

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alice | Bit value | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| | State | → | → | ↑ | ↑ | ↗ | ↗ | ↘ | ↘ |
| Bob | Basis | + | × | + | × | + | × | + | × |
| | Measurement | → | ↗↘ | ↑ | ↗↘ | →↑ | ↗ | →↑ | ↘ |
| | Probability | 100% | 50% | 100% | 50% | 50% | 100% | 50% | 100% |

**Table 10.9** BB84 Example

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alice | Bit value | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| | Basis | + | + | × | + | × | × | × | × |
| Bob | Basis | × | × | × | × | + | + | × | × |
| | Measurement | 0/1 | 0/1 | 0 | 0/1 | 0/1 | 0/1 | 1 | 1 |
| Valid | Basis | *N* | *N* | *Y* | *N* | *N* | *N* | *Y* | *Y* |
| Sifted | Key | | | 0 | | | | 1 | 1 |

**Table 10.10** BB84 Exercise

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alice | Bit value | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 |
| | Basis | + | + | × | × | × | + | + | + |
| Bob | Basis | × | + | + | + | × | × | × | + |
| Valid | Basis | ? | ? | ? | ? | ? | ? | ? | ? |
| Sifted | Key | ? | ? | ? | ? | ? | ? | ? | ? |

has two possible measurement outcomes in Bob's selected measurement basis. For example,

*Exercise 10.8* Alice and Bob chose bases and transmitted bits as indicated in Table 10.9, which for this example yields a shared key of 011. Work out the sifted key by filling in the blocks marked with "?" if Alice and Bob use the bases and transmitted bits in Table 10.10.

Answer:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alice | Bit value | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 |
| | Basis | + | + | × | × | × | + | + | + |
| Bob | Basis | × | + | + | + | × | × | × | + |
| Valid | Basis | *N* | *Y* | *N* | *N* | *Y* | *N* | *N* | *Y* |
| Sifted | Key | | 1 | | | 1 | | | 1 |

**QKD New Trends** Research to develop tamper resistant quantum communications has led to the development of new methods and trends. One view of tamper resistant quantum communications involves the use of distant quantum memories that are entangled. These entangled quantum memories are used to perform a quantum teleportation of message bits from Alice to Bob. Notably, the 2 bits Alice sends to Bob to complete the teleportation operation contains no information about the bit value being teleported. Efforts are also underway to develop "reference frame free" quantum cryptography [41, 42]. Sciarrino et al. [42] experimentally demonstrated quantum information cryptography by using a liquid crystal device (named *q-plate*) that maps polarization encoded qubits into qubits with hybrid polarization-OAM states, which are shown to be invariant under arbitrary rotations around the propagation direction. Another new idea for QKD called "counterfactual QKD" was proposed by Noh [43] that would employ a "nontransmission" of information protocol to allow Alice and Bob to generate a shared quantum key. An experimental demonstration of counterfactual QKD was performed and published in 2012 by the Genovese [44] group and they concluded that there is a possibility to exploit this concept for practical QKD systems. Another new trend is for "alignment-free" quantum communications [42]. By using rotationally invariant quantum states Alice and Bob would not have to spend much effort with ensuring that they have a "shared reference frame." This would be very useful for satellite-to-ground, satellite-to-air, and air-to-satellite quantum communications.

**Concept of Provable Security** Provable security simply means that under a given set of assumptions that no "adversary" exists who can break a security scheme that operates under the stated set of assumptions. For quantum security, the assumptions typically include the "No-Cloning" theorem, that only a single photon or less exists per time-interval and that the adversary "Eve" has not physically taken over Alice's and/or Bob's station.

**Quantum Encryption Advantages Over Classical Encryption** There are several important advantages of quantum encryption over classical encryption. These advantages include secure re-keying, eavesdropper detection, and a basis in the laws of quantum physics for randomness. Another key advantage of quantum encryption is that when a quantum computer becomes available, quantum encryption methods will offer an important means for secure information transmission.

**The Quantum Yuen–Kumar (Alpha-Eta) Scheme** The quantum Alpha-Eta scheme [40, 45] is a means to ensure a quantum level of security at the physical communications transport layer. Alpha-Eta involves using orthogonal quantum states in a large number of bases to enable security. Free-space quantum communications using the Yuen–Kumar Alpha-Eta scheme [45] has been implemented and demonstrated using polarization [40]. The scheme was implemented as follows:
A random basis using preshared keys between sender and receiver is used to chose a randomly rotated basis to transmit and measure the photons. This basis choice encoding amounts to

$$Alice = \begin{vmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{vmatrix} \begin{vmatrix} 0 \\ 1 \end{vmatrix} \Rightarrow Bob = \begin{vmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{vmatrix}^{-1} \begin{vmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{vmatrix} \begin{vmatrix} 0 \\ 1 \end{vmatrix}$$

to encode and recover the bit transmitted. In the example above Alice is sending the message $\begin{vmatrix} 0 \\ 1 \end{vmatrix}$ to Bob and encodes that message in a randomly preshared rotation basis $\theta$. Bob would receive the randomly encoded message and decode the message with the inverse rotation. The value of θ is chosen randomly using preshared keys that are possessed by Alice and Bob. The method has high security because of the extremely large basis space that can be chosen and the method has similar eavesdropping recognition capabilities as other QKD methods. One of the advantages of the Alpha-Eta scheme is that it can function well over existing fiber optic infrastructure.

**Prospects for Non-line-of-sight Atmospheric Quantum Communications** Meyers in 2005 proposed using polarization in the ultraviolet as a means to implement non-line-of-sight (NLOS) free-space quantum communications [46, 47]. Polarization is very robust in atmospheric propagation and the large scattering of UV light is well documented. There have been many NLOS free-space optical communications efforts that demonstrated the ability of UV light to scatter around various obstacles [48, 49]. Combining that scattering capability with polarization encoding as in the Yuen–Kumar scheme [40] would add a further layer of physical security to free-space NLOS optical communications.

**Free-Space Microwave Quantum Communications** Microwaves have been used for many decades for classical communications in free-space [50]. Microwave photons are very low in energy due to their long millimeter to centimeter wavelengths. Nevertheless, microwave photon detectors are sensitive enough to measure microwave photons in free-space. However, there are two key problems. The first problem is that there is a low level cosmic microwave background in the universe [51]. Second is that surrounding the earth there is an additional microwave radiation due to the large amount of microwave communication transmissions worldwide. At the same time, we know that microwave photons will exhibit quantum interference properties like photons at other wavelengths. In addition, it is possible to observe entangled photons at microwave frequencies. Thus, demonstrations of multi-photon microwave interference may provide a pathway to free-space quantum communications with microwaves [52, 53].

**Teleportation** Teleportation is a quantum process whereby quantum information can be transmitted over long distances [54, 55]. As an example of the process of quantum teleportation let us assume that Alice and Bob share half of an entangled photon pair that is in the state $|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|H_A\rangle|V_B\rangle - |V_A\rangle|H_B\rangle\right)$ and that Alice wants teleport to Bob a photon with a defined polarization $|\Omega_C\rangle = \frac{1}{\sqrt{\alpha^2+\beta^2}}\left[\alpha|H_C\rangle + \beta|V_C\rangle\right]$. Alice would perform a joint Bell measurement on her half of the entangled photon pair with the photon she wants to teleport. Prior to the joint-measurement, the state of the three photons is $|\Psi\rangle_{AB} \otimes |\Omega_C\rangle =$

$\frac{1}{\sqrt{2}}(|H_A\rangle|V_B\rangle-|V_A\rangle|H_B\rangle)\otimes\frac{1}{\sqrt{\alpha^2+\beta^2}}(\alpha|H_C\rangle+\beta|V_C\rangle)$. The physics of teleportation describes how the photons of Alice and Bob's entangled pair and the photon to be teleported are changed in Alice's basis to appear as if Alice's photon $|\Psi\rangle_A$ is in an entangled state with $|\Omega_C\rangle$. Using Eq. 10.4 and Eq. 10.5 the three photon state

$$\frac{1}{\sqrt{2(\alpha^2+\beta^2)}}\{\alpha(|H_A\rangle|V_B\rangle|H_C\rangle-|V_A\rangle|H_B\rangle|H_C\rangle)$$
$$+\beta(|H_A\rangle|V_B\rangle|V_C\rangle-|V_A\rangle|H_B\rangle|V_C\rangle)\}$$

can be rewritten as

$$\frac{1}{2}\frac{1}{\sqrt{\alpha^2+\beta^2}}\{|\phi^+\rangle_{AC}\otimes(\alpha|V_B\rangle-\beta|H_B\rangle)+|\phi^-\rangle_{AC}\otimes(\alpha|V_B\rangle+\beta|H_B\rangle)$$
$$+|\psi^+\rangle_{AC}\otimes(-\alpha|H_B\rangle+\beta|V_B\rangle)+|\psi^-\rangle_{AC}\otimes(\alpha|H_B\rangle+\beta|V_B\rangle)\}.$$

Alice has four possible outcomes for her joint measurement of the state $|\Psi\rangle_{AC}$

$$|\Psi^1\rangle=\frac{1}{\sqrt{2}}(|H_A\rangle|V_c\rangle-|V_A\rangle|H_c\rangle)$$
$$|\Psi^2\rangle=\frac{1}{\sqrt{2}}(|H_A\rangle|V_c\rangle+|V_A\rangle|H_c\rangle)$$
$$|\Psi^3\rangle=\frac{1}{\sqrt{2}}(|H_A\rangle|H_c\rangle-|V_A\rangle|V_c\rangle)$$
$$|\Psi^4\rangle=\frac{1}{\sqrt{2}}(|H_A\rangle|H_c\rangle+|V_A\rangle|V_c\rangle)$$

and she would transmit 2-bits to Bob that would instruct him on what transform $T$ to use to operate on his remaining photon of the entangled pair to complete the teleportation. The four cases and operations are 1) $T_1=\begin{bmatrix}1&0\\0&1\end{bmatrix}$, 2) $T_2=\begin{bmatrix}1&0\\0&-1\end{bmatrix}$, 3) $T_3=\begin{bmatrix}0&1\\1&0\end{bmatrix}$ and 4) $T_4=\begin{bmatrix}0&-1\\1&0\end{bmatrix}$. Case 1 is the identity operation and indicates that Bob's photon is in the state of the photon that Alice teleported to him. Case 2 applies a π phase shift to the $|V\rangle$ component of Bob's photon to complete the teleportation. Case 3 rotates the polarizations from $\alpha|H_B\rangle+\beta|V_B\rangle$ to $\alpha|V_B\rangle+\beta|H_B\rangle$, and Case 4 performs an operation similar to Case 3 with a π phase applied shift to the $|H\rangle$ component of Bob's photon.

*Future Teleportation* The US Army has a new basic research focus area developing the underpinning science for mobile quantum information teleportation networks. Initial efforts include the development of an entangled photon and atom teleportation testbed network entitled "A Quantum Network with Atoms and Photons (QNET-AP)" [56]. This research is directed toward developing quantum communications between remote sites that have quantum memories. One of the goals of the US Army demonstration plan is to entangle distant atomic memories between the US Army Research Laboratory (ARL) and the Joint Quantum Institute (JQI) of NIST that are separated by kilometers in free-space and along a fiber optical path. This distance will further allow for a locality loop-hole free test of the Bell inequalities [57, 58]. Another key goal is to develop secure quantum teleportation architectures, schemes, and protocols. This research will lead to the teleportation of quantum information between remote locations and a demonstration of "tamper resistant" quantum communications.

Recently there have been experimental demonstrations of the teleportation of quantum information using free-space optical quantum communications channels. These experiments were performed as precursors to teleportation of quantum information between the ground and satellites. The first took place in China [59] over a 97 km optical path and utilized pointing and tracking systems using lasers at 532 and 671 nm coupled to the entangled photon that is at ~788 nm. GPS was used to enable 1 ns timing accuracy between the remote stations. A wireless classical communications channel was used by Alice and Bob to complete the teleportation protocol. Fidelities from 76 % to 89 % were reported for the teleportation states that were tested. The article also reports that their acquisition, pointing and tracking (APT) system can be applied to any moving object with high accuracy. The second long distance free-space teleportation experimental demonstration took place between the Canary Islands of Tenerife and La Palma with a distance of 143 km [60]. A similar pointing to the one above was used and a 1064 nm free-space optical communications link was employed to instruct Bob on how to complete the teleportation protocol. Timing between the islands was coarsely set using GPS and then fine tuned using an entanglement assisted clock synchronization [61] to achieve 1 ns time accuracy between the locations and a 3 ns coincidence window was used for the measurements. Entanglement fidelities exceeding the classical limit of 67 % were reported. Also noted were conditions of extremely bad weather that prevented some experiments from being conducted.

**Impact of Atmosphere on Quantum Communications** Free-space quantum communications may be negatively influenced due to various atmospheric effects such as turbulence or environmental obscurants like fog or smoke. However, it has been recently demonstrated when using certain entangled photon states that there is a cancellation of turbulence caused angle-of-arrival fluctuations [62]. These angle of arrival fluctuations are a major contributor [63] to the degradation of quantum free-space communication quality. The atmosphere can affect photon absorption, decoherence and/or cause phase distortions. These effects typically lead to a loss of photons that might otherwise be measured at a distant receiver. The atmospheric phase distortions can also modify the quantum state of the transmitted photon. This effect could be interpreted as a potential eavesdropping event in many QKD protocols. The fidelity of quantum communications is a measure of how well the quantum channel preserves quantum information. This is directly tied to the idea of the fidelity of quantum states.

*Atmosphere's Turbulence Effects on Photon Count Fluctuations, Orbital Angular Momentum, Entanglement, Synchronization Accuracy, and Quantum Bit Error Rates* Practical free-space applications of quantum communications and teleportation can be severely limited by atmospheric turbulence that brings about phase distortions, decoherence, and misalignment of transmitters and receivers. Several laboratory and outdoor experiments (see Table 10.15) have addressed how sensitive properties like entanglement and optical angular momentum are to atmospheric fluctuations in temperature and air flow. As an example, Pors et al. [64] determined that the shape of their photon detection coincidence curves were quite robust despite the turbulent conditions they generated in the laboratory. In addition they found that the OAM superposition states could be designed to have an optimal robustness against atmospheric perturbations. Heim et al. [65] showed that the theoretically predicted [66] log-normal transmission probability statistics for entangled photon pairs propagating over a 1.3 km free-space path could be enhanced by defocusing the beam of entangled photons in low atmospheric turbulence and with a highly focused beam of entangled photons in high turbulence. Earlier, researchers at Los Alamos National Laboratory [67] compared calculations of photon count distributions with measurements taken for horizontal propagation paths in weak to moderate atmospheric turbulence conditions and also found that a log-normal distribution best characterizes the probability statistics for single photons. Wu et al. [68] investigated how the atmosphere effects the synchronization accuracy in free-space quantum key distribution (QKD). Their experimental results and calculations showed that synchronization errors come mainly from the intensity fluctuation of synchronized light. By using the constant fraction discrimination method, they found that the synchronization error of a 10 km free-space QKD channel passing through a turbulent atmosphere may be limited within 300 ps which they suggest provides a sufficient synchronization accuracy for long distance free-space QKD, especially satellite-to-ground QKD.

*Coupling the Atmosphere to Propagating Quantum Particles* To properly represent the turbulence physics for the propagation of quantum states in the atmosphere one would need equations of motion for the atmosphere. Typically one would use the Navier–Stokes equations (NSE) with appropriate boundary and initial conditions to represent terrain, urban areas, ambient absorbers and scatterers (i.e., dust, pollution) and the weather conditions. In principle one could use generalized Schrodinger equations to represent the dynamics of the atmosphere as a composite of all the quantum particles making up the atmosphere. In practice currently, the NSE are used to model the atmosphere and Schrodinger like equations are used to govern the motion of the photons that propagate through the atmosphere. This NSE simulated environment would of course have to be coupled to a quantum wavefunction propagator that includes quantum operators representing scattering, absorption, and index of refraction variability.

Free-space quantum communications may involve horizontal or slant path optical propagation. Several investigators have considered the important problem of quantum communications modeling along slant paths through realistic atmospheres, e.g., see Refs. [69, 70]. Some researchers are developing methods that use Wigner functions [71], Maxwell-like equations [72], new types of wavefunctions to represent photons [73, 74], or are describing photon loss at the receiver by proposing annihilation operators that describe losses related to absorption and scattering [65, 75] to model the effects of turbulence and real atmospheric conditions on the free-space propagation of quantum information. Most of these models tend to use Gaussian and Kolmogorov type statistics with a few theoretical investigations into non-Kolmogorov turbulence [69, 70]. Of course, since the atmosphere is nonstationary, inhomogeneous, and anisotropic, models will have to improve beyond the Kolmogorov models to reasonably represent the impact of turbulence on free-space quantum communications in general diurnal and seasonal varying conditions. In the following section we present experiments for free-space atmospheric quantum communications that are the beginning database for verifying free-space quantum communications models.

## 10.3 Free-Space and Atmospheric Quantum Communications Experiments

### *10.3.1 Introduction*

Quantum communications (QC) is a field growing in importance. QC applications are expected to play a vital role in both the domestic and defense sectors. While fiber optic implementations of quantum communications technologies are being tested for communications infrastructure it is important to also consider free-space quantum communications that will play an important role in applications such as earth-to-satellite, end-of-line connections, and defense implementations. Quantum communications has the potential to provide enhanced security, bandwidth, and speed for free-space communications. Today's free-space quantum communications technologies accomplish transmission and detection of photons over long distances. Earlier ground-to-space laser communications experiments were important because they showed that such measurements were feasible. For example, Alley et al. [76] reported on the initial measurements retrieved from the 1969 Apollo 11 Lunar Laser Ranging Experiment conducted between a lunar retroreflector and the McDonald Observatory. Subsequently, more elaborate laser optic communications experiments were conducted, for example, in the USA and Japan, to demonstrate the capability to establish optical communication links to low earth orbiting satellites from the ground [77–81]. These later experiments also provided a platform from which to measure the effects of atmospheric turbulence on long distance laser propagation. To survey QC technological trends this section will highlight representative free-space quantum communications field experiments conducted over the past decade, to include experiments along horizontal propagation paths of varying distances, communication paths from ground-to-aircraft, ground-to-space, and in the laboratory.

### *10.3.2 Ground-to-ground, Ground-to-aircraft and Ground-to-satellite Experiments*

Table 10.11 provides a summary of representative quantum communications field experiments along free-space propagation paths of varying distances. (A list of abbreviations used in Table 10.11 is provided in Table 10.12) Most of these experiments were conducted to implement and test various methods for quantum key distribution (QKD) in real-world atmospheric conditions. Several free-space QKD experiments were performed over horizontal distances from 0.7–1.6 km, such as those reported in [65, 82–89]. Much longer distance experiments were also conducted, most notably the quantum communications experiments across a 144 km path in the Canary Islands [90–93] and the QKD experiments over 20-, 40- and 96 km paths in China [94, 95]. One of the first practical free-space QKD experiments was conducted in daylight and nighttime conditions over a 10 km path by the Los Alamos National Laboratory (LANL) as reported by Hughes et al. [96, 97]. LANL provided in [98] a tabular summary of primary groups investigating QKD through free-space at that time. More recent QKD experiments have also demonstrated the capability to operate in daylight conditions, e.g., Refs. [99, 100]. Another free-space quantum key distribution system that was designed for daylight high-speed quantum key transmission (1 Mbps) in urban areas was reported by Garcia-Martinez et al. in [89]. Furthermore, a U.S. government sponsored project in 2009 reported a free-space quantum encryption (QE) experiment over distances up to 20 km from the ground to a flying aircraft at 10,000 feet [101]. Here, the Alpha-Eta encryption method [40, 45] was implemented and combined with advanced free-space optical terminals to send information (preshared keys) by quantum means and produce a Gbit/s air-to-ground optical link. The German Aerospace Center and their university collaborators also reported on a free-space experiment over a 20 km distance from the ground-to-aircraft conducted in March 2011 [102, 103]. In this QKD experiment, Nauerth et al. [102, 103] used attenuated laser pulses and polarization encoding to establish a 10 min. stable link producing a sifted quantum key rate of 145 bits/s with a quantum bit error rate (QBER) of 4.8 %. In contrast, Temporao et al. [104] reported on a 1.5 km QKD study operating at a mid-infrared wavelengths to mitigate adverse foggy conditions (Figs. 10.2 and 10.3).

**Table 10.11** Summary of Representative Free-Space Quantum Communications Field Experiments

| Date | L(km) | Speed | Tech | λ(nm) | LPR | KP | QBER | Reference |
|---|---|---|---|---|---|---|---|---|
| 2013 | 0.3 | 0.93 Mbps | QKD | 850 | 1.5 GHz | B92 | 2.17% | García-Martínez [89] |
| 2013 | 9.3, 12.3 | – | QC | 850 | 50 MHz | BC | 1% | Liu [107] |
| 2013 | 7.8 | 0.42 b/s | QKD | 811 | – | BB84 | – | Cao [113] |
| 2012 | 20, 40<br>96 | 268, 159.4<br>48 b/s | QKD | 850 | 100 MHz | BB84 | 2.35, 2.73<br>4.04% | Wang [94, 95] |
| 2012 | 143 | – | QTel | 808(404) | – | – | – | Ma [112] |
| 2012 | 97 | – | QTel | 788(394) | – | – | – | Yin [59] |
| 2011 | 20 | 145 b/s | QKD | 1550 | – | BB84 | 4.8% | Nauerth [102, 103] |
| 2011 | 1.6 | – | QKD | 809 | – | – | – | Heim [88] |
| 2011 | 1.3 | – | QKD | 815 | – | B92 | – | Heim [65] |
| 2010 | 16 | – | QTel | 810 | – | – | – | Jin [111] |
| 2010 | 1.2 | – | QKD | 670 | – | BB84 | – | Benton [99] |
| 2010 | 1.305 | 2.7 kb/s | QKD | 808 | – | B92 | 2.48% | Erven [114] |
| 2010 | 1.0 | – | QKD | 809 | – | – | – | Heim [116] |
| 2009 | 1.065 | 240 kb/s | QKD | 1500 | – | B92 | 0.57% | Toyoshima [87] |
| 2009 | 20 | 2.5 Gb/s | QE | – | – | A–E | – | NuCrypt [101] |
| 2009 | 1.5 | 2.2 Mb/s | QKD | 850 | 1.25 GHz | BB84 | 3.1% | Bienfang [86] |
| 2009 | 0.350 | 385 b/s | QKD | 813 | – | B92 | – | Peloso [100] |
| 2009 | 144 | – | QKD | 810 | – | – | 3.85% | Fedrizzi [90] |
| 2009 | 0.08 | 17 kb/s | QKD | 850 | – | BB84 | 2.3% | Peev [117] |
| 2009 | 0.1 | 3.2 kb/s | QKD | 809 | 100 kHz | C–V | – | Elser [118]<br>Heim [119] |
| 2008 | 1.5 | – | QKD | 4600 | 750 kHz | BB84 | 2.3% | Temporao [104] |

**Table 10.11** (Continued)

| Date | L(km) | Speed | Tech | λ(nm) | LPR | KP | QBER | Reference |
|---|---|---|---|---|---|---|---|---|
| 2007 | 1.525 | 85 b/s | QKD | 815 | – | B92 | 4.92% | Erven [82] |
| | | | | | | | | Erven [83] |
| | | | | | | | | Weihs [120] |
| 2006 | 0.48 | 50 kb/s | QKD | 850 | – | BB84 | 3.0–5.0% | Weier [121] |
| 2006 | 1.5 | 200 b/s | QKD | 810 | – | E91 | 4.0% | Marcikic [84] |
| | | | | | | | | Ling [122] |
| | | | | | | | | Ling [123] |
| 2006 | 144 | 12.8 b/s | QKD | 710 | 249 MHz | BB84 | 6.48% | Ursin [91] |
| | | 42 b/s | | | 10 MHz | | | Schmitt [92] |
| | | | | | | | | Zeilinger [124] |
| 2005 | 6.5 | – | QKD | 830 | 1 MHz | – | 6.5% | Panthong [125] |
| 2004 | 7.8 | – | PE | 810 | – | – | 9.9% | Resch [109] |
| 2004 | 13 | 10 b/s | QKD | 702 | – | BB84 | 5.83% | Peng [126] |
| 2004 | .730 | 1 Mb/s | QKD | 845 | 10 GHz | B92 | 1.1% | Bienfang [85] |
| 2003 | 0.6 | – | PE | 810 | – | – | 8.4% | Aspelmeyer [108] |
| | | | QTel | | | | | Ursin [110] |
| 2002 | 23.4 | – | QKD | – | – | – | – | Kurtsiefer [127] |
| 2002 | 9.81 | – | QKD | 772 | – | BB84 | 5.0% (d) | Hughes [96,97] |
| | | | | | | | 2.1% (n) | |
| 2002 | 4.0 | – | QKD | 835 | – | – | – | Edwards [128] |

**Table 10.12** List of Abbreviations

| Abbreviation | Definition |
|---|---|
| L (km) | Distance (in kilometers) |
| Tech | Technology of interest |
| λ (nm) | Wavelength (in nanometers) |
| LPR | Laser pulse rate |
| QKD | Quantum key distribution |
| CQKD | Counterfactual QKD |
| KP | QKD protocol |
| QTel | Quantum teleportation |
| QBER | Quantum bit error rate |
| PE | Polarization entanglement |
| NS | No-switching |
| SKE | Secret key encryption |
| C-V | Continuous variable |
| (d)/(n) | daytime/nighttime |
| BC | Bit commitment |
| QE | Quantum encryption |
| A-E | Alpha-Eta |
| – | No data |

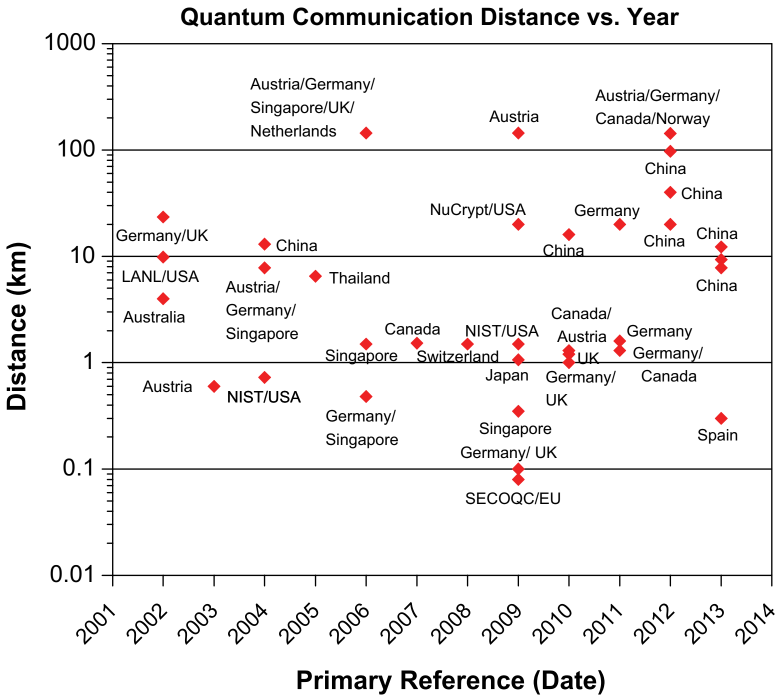


**Fig. 10.2** Quantitative relationship between the propagation distance and the year the free-space quantum communication experiment was executed.

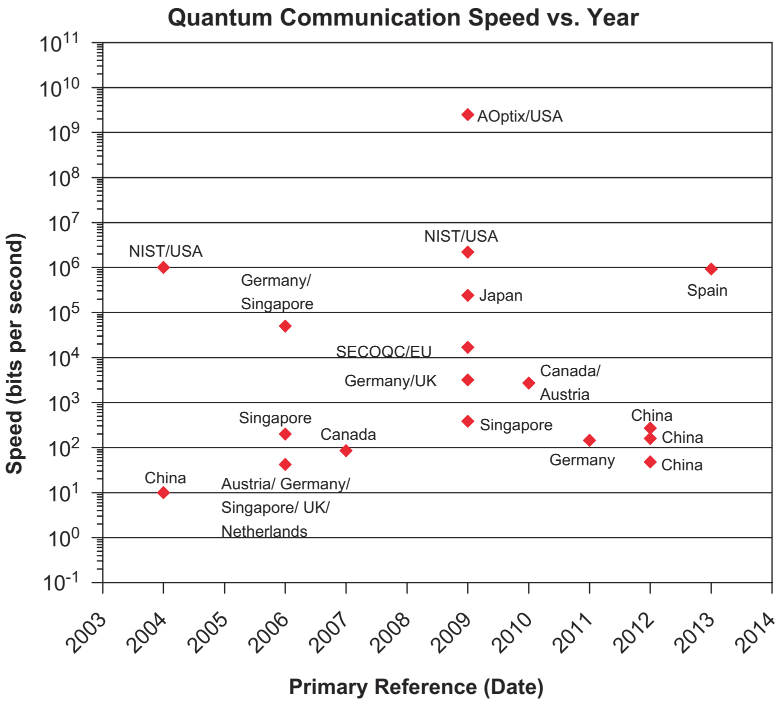


**Fig. 10.3** Quantitative relationship between the transmission speed achieved and the year the free-space quantum communication experiment was executed.

Figure 10.2 shows a graph of the quantitative relationship between the propagation distances of the field experiments and the year the experiments were executed, which includes information on the country/sponsor. In Table 10.11 we also show that the field experiments implemented varying quantum protocols (e.g., BB84, B92, E91, C-V, Alpha-Eta) and varying light source wavelengths ($\lambda = 394$-$404$ nm, $\lambda =$ 670-850 nm, $\lambda = 1.5\ \mu m$ and $\lambda = 4.6\ \mu m$). The available data also show that achieved transmission speeds ranged from 10 bits/s to 2.5 Gbits/s (see Fig. 10.3).

Regarding QKD new trends, Liu et al. [105] reported on a measurement-device-independent QKD protocol that generated more than a 25 kbit secure key over a 50 km fiber link. This was a proof-of-principle experimental demonstration of secure quantum communications with implications for both fiber and free-space quantum channels. At the same time, Gisin et al. [106] reported on experimental demonstration of secure "bit commitment" between their locations in Geneva and Singapore based on quantum communications and special relativity. With the bit commitment (BC) protocol, Bob commits a secret bit to Alice at a given instant which he can choose to reveal some time later. Here, Bob's bit is perfectly concealed from Alice until he decides to open the commitment and reveal his bit to Alice. A free-space experimental demonstration of quantum communications (QC) using bit commitment (BC) protocols between two stations separated by more than 20 km was reported in [107].

**Table 10.13** Quantum Communications Experiments to Satellites

| Date | L(km) | Speed | TECH | λ(nm) | LPR | KP | QBER | Reference |
|---|---|---|---|---|---|---|---|---|
| 2013 | 400 | – | Single photon Exchange | 702 | 76 MHz | – | – | Yin [131] |
| 2009 | 1000 | – | Photon beam Polarization | 808-847 | – | – | – | Toyoshima [81] |
| 2008 | 1485 | – | Single photon Exchange | 532 | 17 kHz | – | – | Villoresi [129] Bonato [130] |
| 2006 | 610 | – | Photon beam APD, CCD | 808-847 | – | – | – | Toyoshima [79] |

The remaining free-space experiments listed in Table 10.11 relate to long distance polarization entanglement experiments and demonstrations of quantum teleportation, such as those reported in [59, 108–113]. In addition, Erven reported on a QKD practical application using an improved entangled photon source [114] and Franson [115] presented a paper on quantum communications using entangled photon holes (EPH), which have the unique property of being relatively insensitive to photon loss and amplification. Franson [115] suggested that these features of EPH may be beneficial for QKD applications.

Table 10.13 above describes demonstration experiments related to single photon and photon beam exchanges from ground to space as reported in [79, 81, 129, 130, 131]. In these ground-to-satellite experiments, photon measurements were able to detect returns from a low earth orbiting satellite whose orbit's heights were 610 km, 1485 km, 1000 km, and 400 km respectively. Using high accuracy timing, high repetition rate pulses and narrow field of view receiver optics Yin et al. [131] reported achieving high signal-to-noise ratio (SNR) of 16:1. In contrast, high transmission losses in a 2008 single photon exchange experiment [129] prevented the successful implementation of a QKD protocol. Note that future ground-to-space QKD experiments, e.g., SEcure COmmunication based on Quantum Cryptography (SECOQC) and Space-QUEST: Quantum Entanglement for Space Experiments, have been proposed by the European Space Agency (ESA) and its collaborators from Austria, Belgium, Germany, UK, Canada, Switzerland, Czech Republic, France, Russia, Sweden, and Italy [132, 133]. Similarly, Scheidl et al. [134] reported on a proposal to perform quantum communication experiments over a distance of 400 km from the ground-to-space using the International Space Station.

*Single Photon Detectors* The performance of quantum communications systems significantly depends on detection efficiency and noise reduction. Development of many new products is ongoing in various locations for use in QKD and other quantum technology applications. For example, Ma et al. [135] reported that the National Institute of Standards and Technology (NIST) had developed a low noise up-conversion detector for 1310 nm using a LiNbO3 (PPLN) waveguide. In their setup, the 1310 nm signal photon is upconverted to 710 nm in the PPLN waveguide pumped by a 1550 nm laser, which is then detected by a low noise Si-APD single photon detector. NIST has integrated the upconversion Si-APD detector into various QKD systems and have performed both single photon and entangled photon pair measurements. In [135], NIST shows a comparison of performance speeds and other characteristics of the main single photon detectors (i.e., those currently available) and the Si-APD upconversion detector that they developed at NIST. Their comparison also includes information related to two types of superconducting single photon detectors, i.e., the transition edge sensor (TES) and the superconducting single-photon detector (SSPD), which can work in the near-infrared range. More recently, Fejer et al. [136] report on upconverson and single photon detection near 2 microns.

#### 10.3.2.1 Representative Quantum Communications Experiments (QKD and Polarization Entanglement) in the Laboratory

Table 10.14 provides information on representative quantum communications experiments (QKD and polarization entanglement) in the laboratory across varying table top propagation paths ranging from 0.5–4.0 meters in distance. Several experiments reported transmission speeds varying from 3.5 kb/s to 25 Mb/s [137–142]. The experiments implemented varying light source wavelengths from visible ( $\lambda =$ 632 nm) to near-infrared ( $\lambda = 1550$ nm). Most of these laboratory experiments implemented the BB84 QKD encryption protocol. An exception was the continuous-variable (C-V) QKD experiment reported in Ref. [143]. Ralph and Lam [22] suggested that C-V methods for QKD can offer distinct advantages over single photon approaches, such as implementation of deterministic teleportation protocols. Finally, Genovese et al. [44] reported on a experimental demonstration of counterfactual quantum cryptography (CQKD) in the laboratory, wherein information is transferred securely between Alice and Bob even when no photons or other quantum particles carrying the information are in fact transmitted between them. Additional discussion on counterfactual quantum communications can be found in Refs. [43, 144].

**Representative Studies Related to Atmospheric Turbulence Effects on Quantum Communications Experiments** Table 10.15 presents representative studies related to atmospheric turbulence effects on QC experiments to include effects on QKD and single photon statistics. Some of the key interests in recently published papers relate to photon count fluctuations, orbital angular momentum entanglement, optical vortex beams, synchronization accuracy, and quantum bit error rates. In certain quantum processes the adverse effects of turbulence can be mitigated and we expect that these features can be moved to quantum communications [19, 146, 147].

**Quantum Repeaters and Quantum Memory** Table 10.16 presents a representative list of recent efforts related to quantum repeaters and quantum memory to include information on the research groups, investigators, experimentally demonstrated coherence times and distance of entanglement of atoms/ions. As an example, Rolston and his colleagues at the Joint Quantum Institute (UMD/NIST) are using atomic ensembles to investigate problems in quantum communications and quantum memory. [152, 153]. Similarly, Kuzmich et al. at the Georgia Institute of Technology are conducting quantum communications experiments related to atom-photon entanglement with quantum memories reported on the time scale of one

**Table 10.14** Quantum Communications Experiments in the Laboratory

| Date | L(m) | Speed | TECH | λ(nm) | Sponsor | KP | QBER | Reference |
|---|---|---|---|---|---|---|---|---|
| 2012 | – | – | CQKD | 812 | INRIM/Italy | N09 | 12.0 % | Genovese [44] |
| 2010 | 4.0 | – | QKD | 670 | UK | BB84 | 4.0 % | Benton [99] |
| 2009 | 0.6 | – | PE | 702 | ORNL/USA LANL/USA | – | – | Humble [145] |
| 2008 | 3.4 | 8.13 kb/s | QKD | 860 | Japan | BB84 | 5.5 % | Toyoshima [138] |
| 2006 | 0.5 | 3.5 kb/s | QKD | 632 | UK | BB84 | – | Godfrey [139] |
| 2006 | 0.5 | – | QKD | 1550 | Japan | C-V | – | Hirano [143] |
| 2006 | 0.7 | 3.8 kb/s | QKD | 830 | Russia | BB84 | – | Kurochkin [142] |
| 2005 | – | 25 Mb/s | QKD | 1064 | Australia | NS | – | Lance [140] Sharma [141] |
| 2002 | – | 200 kb/s | QKD | 670 | Northwestern Univ/USA | SKE | – | Barbosa [137] |

**Table 10.15** Atmospheric Turbulence Effects on Quantum Communications Experiments

| Date | Purpose | Key interest | Reference |
|---|---|---|---|
| 2012 | Single photon propagation through turbulence, beam scintillation, angle of arrival statistics | Impact of atmosphere on long-range quantum communications | Capraro [93] |
| 2011 | Entangled photon propagation through turbulence | Atmospheric effects on entanglement properties | Heim [65] |
| 2009 | Quantum light propagation through turbulence | Nonclassical photon-statistics | Semenov [65, 75] |
| 2009 | Photon propagation through turbulence | Orbital-angular-momentum entanglement | Pors [64] |
| 2009 | Photon propagation through turbulence | Optical vortex beams | Tyler [148] Boyd [149] |
| 2007 | Single photon statistics, propagation through turbulence | Reduce photon count fluctuations | Berman [150] |
| 2007 | QKD through atmosphere, 650 nm | Synchronization accuracy | Wu [68] |
| 2007 | QKD through turbulence | Turbulence effects on QBER | Yan [151] |
| 2004 | Single photon statistics, Propagation through turbulence | Experimental validation of theory | Milonni [67] |

minute [154, 155]. Note that the longest reported distance entanglement for atoms and photons is 300 m in an optical fiber-based quantum communication channel [156].

### *10.3.3 Summary*

A review of representative free-space quantum communications field experiments was presented and discussed relating to the trends in quantum technology development, so vital for future enhanced security communications in both the domestic and defense sectors. The highlighted free-space quantum communications field experi-

**Table 10.16** Recent efforts related to Quantum Repeaters and Quantum Memory

| Research group | Investigators | References | Coherence Time |
|---|---|---|---|
| Univ. of Michigan, | L. Duan, C. Monroe, | Moehring [57] | – |
| Ann Arbor, MI | D. Moehring, P. Maunz, | Duan [157, 158] | |
| Joint Quantum Institute | S. Olmschenk, K. Younge, | | |
| (JQI), UMD/NIST | D. Matsukevich | | |
| College Park, MD | | | |
| Joint Quantum Institute | R. Willis, F. Becerra, | Willis [152] | – |
| (JQI), UMD/NIST | L. Orozco, S. Rolston | Rolston [153] | |
| College Park, MD | | | |
| Georgia Institute | A. Radnaev, Y. Dudin, | Radnaev [159] | 0.1 s |
| of Technology | R. Zhao, H. Jen, | Dudin [160] | 10 ms |
| Atlanta, GA | S. Jenkins, A. Kuzmich, | Dudin, Kuzmich [155] | 16 s |
| | T. Kennedy, A Radnaer, | Li [154] | |
| | J. Blumoff, L. Li | | |
| California Institute | H. Kimble, K. Choi, | Kimble [2] | 8 $\mu s$ |
| of Technology (CIT) | H. Deng, J. Laurat | Choi [161] | |
| Pasadena, CA | | | |
| Institut fur Quantenoptik, | G. Buning, J. Will, | Buning [162] | 21 s |
| Leibniz Universitat, | W. Ertmer, E. Rasel, | ($^{87}$Rb) | |
| Hannover, Germany; | C. Klempt, J. Arlt, | | |
| Asrhus U., Denmark; | F. Martinez, | | |
| CNRS, France | F. Piechon | | |
| Massachusetts Institute | T. Peyronel, O. Firstenberg, | Lukin [163] | – |
| of Technology (MIT), | Q-Y Liang, S. Hofferberth, | | |
| Harvard U., CIT, Max | A. Gorshkov, T. Pohl, | | |
| Planck Institute | M. Lukin, V. Vuletic | | |
| CNRS, France | C. Deutsch, F. Ramirez, | Deutsch [164] | 58 s |
| | C. Lacroute, F. Reinhard, | ($^{87}$Rb) | |
| | T. Schneider, J. Fuchs, | | |
| | F. Piechon, F. Laloe | | |
| CNRS, France; | N.Sangouard, C.Simon, | Sangouard [26] | 300 m distance |
| U. Geneva, Switz.; ICFO, Spain; | H. Riedmatten, N. Gisin, | Yuan [156] | entanglement |
| Hefei Nat'l Lab & USTC, China; | B. Zhao, Y-A Chen, | Sangouard [25] | of Rb atoms |
| Inst. Theor. Phys., | J.-W. Pan, Z-S Yuan, | Jin [165] | 200 ns |
| Heidelberg, Germany; | S. Chen, J. Schmiedmayer, | Yang [166] | 28 ms |
| U. Innsbruck, Austria; | F. Yang, M. Torston, | | |
| U. Vienna, Austria | C. Lutz | | |
| U. Calgary, Canada; | | | |
| U. Geneva, Switz. | | | |
| Laboratory Quantum | L.-M. Duan, M.D. Lukin, | Duan [167] | DLCZ scheme |
| Communication & Computation, | J. I. Cirac, P. Zoller | Zhao [168] | |
| Hefei, China; | B. Zhao, M. Müller, | | |

**Table 10.16** (Continued)

| Research group | Investigators | References | Coherence |
|---|---|---|---|
| Harvard Univ,Cambridge, MA; | K. Hammerer, P. Zoller | | |
| Inst. Theor. Phys., Innsbruck, | | | |
| Austria | | | |
| Niels Bohr Institute, Denmark; | H. Specht, C. Nolleke, | Specht [169] | 180 $\mu s$ |
| Max Planck Institute, Germany; | A. Reiserer, M. Uphoff, | Julsgaard [170] | 4 ms |
| U. Brussels, Belgium; | E. Figueroa, S. Ritter, | | |
| Palacky U., Czech Republic | G. Rempe, B. Julsgaard, | | |
| | J. Sherson, I. Cirac, J. Flurasek, E. Polzik | | |
| Inst. Exper. Phys., U. Innsbruck, | L. Slodička, G. Hétet, | Slodička [171] | 1 m distance entanglement |
| Austria | N. Röck, P. Schindler, M. Hennrich, R. Blatt | | of trapped atomic ions |

ments have also demonstrated the feasibility and practical use of free-space QKD systems, quantum teleportation and single photon exchange over extremely long distances. Progress has been achieved to operate high-speed free-space QKD systems during both daylight and nighttime hours, wherein previously communication links were difficult to establish during the day with high background light. Future ground-to-aircraft and ground-to-space quantum experiments will provide additional progress toward achieving highly secured worldwide communication networks. Continued development of improved entangled photon sources, photon detection systems, and improved encryption algorithms will make such free-space quantum communication technologies as quantum teleportation and QKD more efficient, more practical and more secure. For example, the US Army Research Laboratory (ARL) has been developing quantum communication technologies (see Refs. [56, 172, 173, 174]) and is expected to perform additional experiments and develop advanced technologies supporting free-space quantum communications applications.

Recently two notable free space and atmospheric quantum communications experiments have been performed. A quantum nonlocality experiment by Jennewein et al. [175] connected three quantum communications nodes. The nodes shared entanglement that was distributed from one node to two distant nodes that were 772 m and 686 m through a free space link. This experiment was a precursor to other applications such as multi-party quantum secret sharing and multi-party teleportation. Another experiment was performed by Vallone et al. [176] that simulated quantum key distribution from satellites using retro-reflectors mounted on five low earth orbit satellites. Their experiments concluded that their QBER rates were in a range suitable for QKD. They further proposed an alternative QKD scheme that would have a small impact on satellite payload. Also see Jennewein et al. [177] regarding advances towards a quantum communications satellite.

### 10.3.4 Exercises

**Quantum Teleportation** *Exercise 10.9* Let us assume that Alice and Bob share half of an entangled photon pair and that Alice wants to teleport to Bob a horizontal photon $|H\rangle$. The teleportation operation takes place when Alice performs a joint Bell measurement on her half of the entangled photon pair with the photon that she wants to teleport. Please explain.

**Impact of Atmosphere on Quantum Communications** *Exercise 10.10* Several methods have been experimentally demonstrated to help mitigate (a) single photon transmission loss and (b) entangled photon decoherence due to the negative impacts of atmospheric turbulence or environmental obscurants like fog or smoke. Give at least five examples.

*Exercise 10.11* Has the impact of the atmosphere been the most important consideration in determining the laser light wavelength(s) for free-space quantum communications field experiments? Please explain.

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